JINA-CEE

Center for the Evolution of the Elements

March 2021

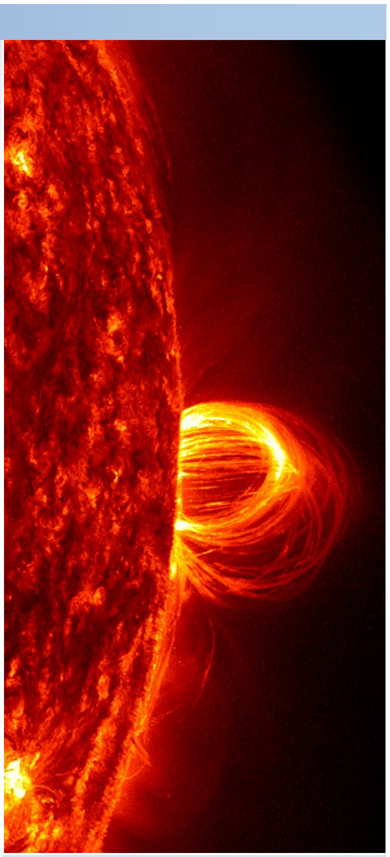


Image credit: NASA/GSFC/SDO

A note from the Director, Hendrik Schatz

Dear Members of the JINA-CEE Community and Friends,

The JINA-CEE and IReNA communities have been very active despite the ongoing challenges related to in-person collaboration and communication. I would like to thank everybody for their contributions under often difficult circumstances. As you can see in this newsletter, exciting science continues to come from our unique interdisciplinary collaborations. We are also working on a community white paper laying out the future scientific challenges in nuclear astrophysics and the extraordinary opportunities to address them. A writing team is working hard on a first draft based on community input from the JINA Horizons conference in December and community input continues to be welcome. I am also happy to report that the collaboration has developed a number of creative and innovative virtual events planned for the near future to bridge the time until we can have in-person meetings again. These events will be announced on the JINA-CEE and IReNA websites so make sure you don't miss them. They will move collaborative science forward and offer young scientists important networking opportunities. In that vein, I also invite you to join the JINA-CEE/IReNA international online seminars, which now offer opportunities for informal interactions with the speakers before and after the event. Thank you to the international and interdisciplinary group of postdocs who are currently organizing the series: P. Gastis (JINA-CEE US, chair), Y. Lim (EMMI Germany), C. Mondal (ChETEC France), N. Nishimura (Ukakuren Japan), Z. Prudil (SFB-881 Germany), A. Psaltis (NuGRID Germany), and M. Saxena (JINA-CEE US).

I hope you enjoy this newsletter, and as always don't hesitate to get in touch with questions or ideas.

Inside this issue

Lifetime measurements of excited states in ^{15}O to peek into the solar core

Contributed by Bryce Frentz (University of Notre Dame, USA)

The carbon-nitrogen-oxygen (CNO) cycle (Fig. 1) is the main energy source in stars more massive than our sun and defines their energy production. The overall rate of the CNO cycle constrains the lifetimes of massive stars and is an important component for determining the age of globular clusters.

In our Sun, the CNO cycle accounts for roughly 1% of the total energy production. While this may not seem like much, studying these fine margins can provide important information about the Sun's metal content (or metallicity). The neutrinos produced by the CNO cycle can be detected on Earth and provide a unique probe into the solar core. These neutrino fluxes depend not only on the isotopic abundances, but also on their associated, individual reaction rates, like those of ^{14}N(p,γ)^{15}O and ^{12}C(p,γ)^{13}N.

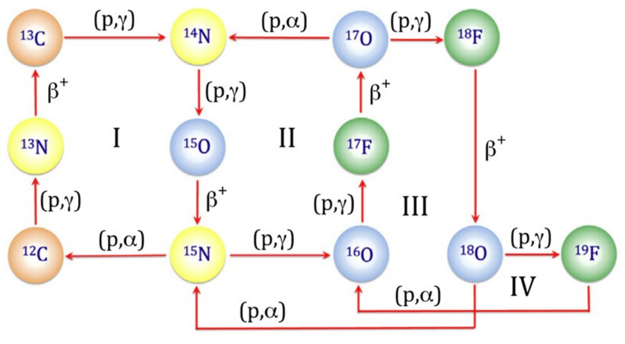


Figure 1. The CNO cycles are one source of energy in stellar cores. In the Sun, cycle I accounts for roughly 1% of the total energy produced in the core but is critical to understand the solar composition.

Recently, the BOREXINO collaboration succeeded in the first measurement of the solar CNO neutrino component, coming primarily from the beta-decay of ^{15}O nuclei [1]. Due to its importance, extensive efforts have been undertaken to reliably determine the ^{14}N(p,γ)^{15}O reaction rate at the solar energy range. The uncertainty in the reaction rate arises predominantly from the uncertainty in the lifetime of the state at Ex = 6792 keV in ^{15}O [2]. Previous measurements of this state's lifetime are discrepant or only upper bounds, and some suffer from large systematic uncertainties. In order to address this, a new measurement of this state's lifetime, as well as those from the excited states at Ex = 5181 keV and Ex = 6172 keV, has been performed using the Doppler Shift Attenuation Method (DSAM) at the Nuclear Science Lab at the University of Notre Dame. To increase the effect, the measurement was performed at higher energies than previous measurements to increase Doppler shift of the de-excitation gamma-rays.

The lifetimes were measured with three different targets each, and we report the weighted average. For the 6792 keV state, we obtained a $\tau = 0.6 \pm 0.4$ fs. This measurement agrees with the published upper bounds while providing a finite value and more stringent constraint on the lifetime (Fig. 2). To provide cross-validation of our method, we measured the lifetimes of the states at 5181 keV and 6172 keV to be $\tau = 7.5 \pm 3.0$ and $\tau = 0.7 \pm 0.5$ fs, respectively, in good agreement with previous measurements. These new lifetimes will be used alongside recent measurements of the ^{14}N(p,γ)^{15}O reaction capture cross-section in a full *R*-matrix fit to extrapolate the reaction's behavior to solar energies. These results will provide a more complete understanding of this crucial reaction and an important, independent verification of the recent solar neutrino measurements.

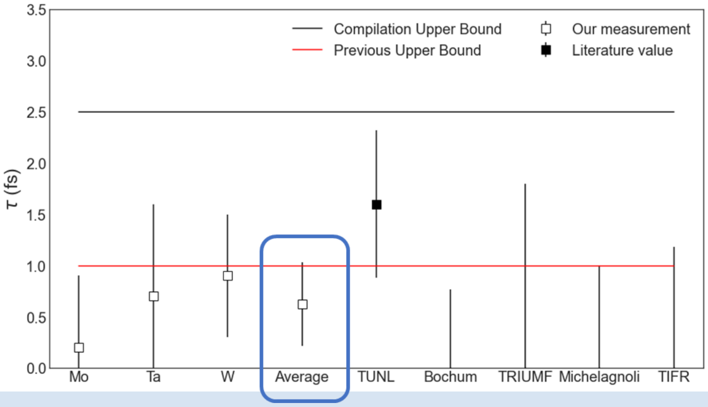


Figure 2. Lifetimes of the 6.79 MeV state in ^{15}O obtained in this work compared with previous measurements. Shown are the individual measurements for our three targets and the reported, weighted average.

Further reading: Frentz et al., accepted to PRC. https://arxiv.org/abs/2012.13029

References:

[1] The Borexino Collaboration., Agostini, M. et al., Nature 587, 577–582 (2020)

[2] Li et al., Phys. Rev. C 93, 055806 (2016)

Meteorites Remember Conditions of Stellar Explosions

Contributed by Benoit Côté (Konkoly Observatory, Hungary)

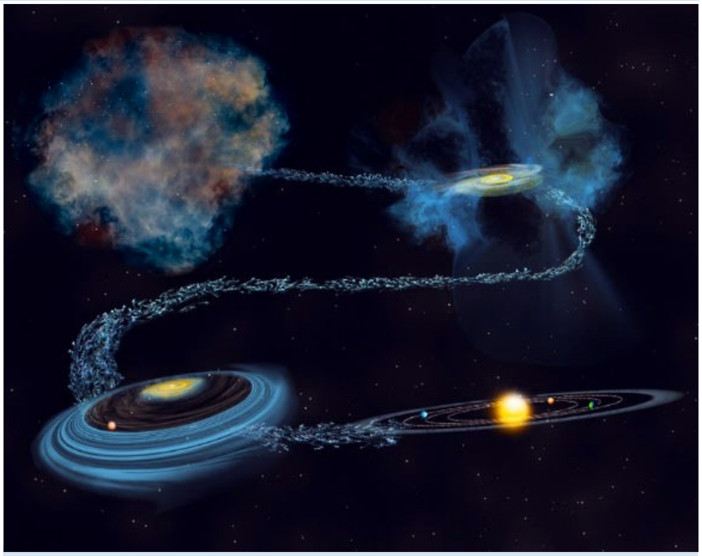


Figure 1: Artist illustration of the formation of the solar system, capturing the moment where radioactive nuclei got incorporated into solids that would become meteorites. Image credit: Bill Saxton / NSF / AUI / NRAO

The question of which astronomical events can produce the heaviest elements has been a mystery for decades. Today, it is thought that they were synthesized by the r process during violent collisions between two neutron stars, between a neutron star and a black hole, or during rare explosions following the death of massive stars. Some of the nuclei produced by the r process are radioactive and take millions of years to decay into stable nuclei. Iodine-129 and curium-247 are two of such nuclei that were produced before the formation of the sun. They were incorporated into solids that eventually fell on the earth's surface as meteorites. Inside these meteorites, the radioactive decay generated an excess of stable nuclei. Today, this excess can be measured in laboratories in order to figure out the amounts of ^{129}I and ^{247}Cm that were present in the solar system just before its formation.

Why are these two r-process nuclei so special? They have a peculiar property in common: they decay at almost exactly the same rate. In other words, the ratio between ^{129}I and ^{247}Cm has not changed since the creation of these isotopes, billions of years ago.

A team of international researchers led by JINA-CEE and IReNA members took advantage of this amazing coincidence. Lead author Benoit Côté says "With the ^{129}I to ^{247}Cm ratio being frozen in time, like a prehistoric fossil, we can have a direct look into the last wave of heavy element production that built up the composition of the solar system".

Iodine, with its 53 protons, is more easily created than curium with its 96 protons. As a consequence, the ^{129}I to ^{247}Cm ratio highly depends on the amount of neutrons that were available during their creation.

The team calculated the ^{129}I to ^{247}Cm ratios synthesized by compact binary mergers to find the right set of conditions that reproduce the composition of meteorites. They concluded that the amount of neutrons available during the last r-process event before the birth of the solar system could not be too high. Otherwise, too much curium would have been created relative to iodine. This implies that very neutron-rich sources likely did not play an important role.

While the researchers could provide new and insightful information regarding how these r-process nuclei were made, they could not pin down the nature of the astronomical object that created them. This is because nucleosynthesis models are based on uncertain nuclear properties, and it is still unclear how to link neutron richness to specific astrophysical sites such as massive star explosions and colliding neutron stars. "But the ability of the ^{129}I to ^{247}Cm ratio to peer more directly into the fundamental nature of heavy element nucleosynthesis is an exciting prospect", says Nicole Vassh, coauthor of the study.

With this new diagnostic tool, advances in the fidelity of astrophysical simulations and in the understanding of nuclear properties could reveal which astronomical objects participated in the creation of the heaviest elements of the solar system.

"Studies like this are only possible when you bring together a multidisciplinary team, where each collaborator contributes to a distinct piece of the puzzle. The JINA-CEE 2019 Frontiers meeting provided the ideal environment to formalize the collaboration that led to the current result," Côté said.

Further Reading: Côté , B. et al, *Science* 26 Feb 2021, Vol. 371, Issue 6532, pp. 945-948. DOI: 10.1126/science.aba1111

Nuclear Physics through Stellar Seismology

Contributed by Morgan Chidester (Arizona State University, USA)

Photons emitted from stellar surfaces and neutrinos released from stellar interiors may not directly reveal all that we want to know about the internal constitution of the stars. For example, a direct view of the chemical stratification from the core to the surface is hidden. These interior abundance profiles matter: they impact a star's opacity, thermodynamics, and nuclear energy generation. In addition, sound waves can resonate inside a star. We see these resonances as rhythmic changes, as pulsations, in the star's luminosity

Most of a main-sequence star's initial metallicity comes from the carbon, nitrogen and oxygen (CNO) inherited from its ambient interstellar medium. All of the CNO abundances pile up at nitrogen during hydrogen-burning on the main-sequence because the ^{14}N(p,γ)^{15}O reaction rate is the slowest step in the hydrogen-burning CNO cycle. During the ensuing helium-burning phase, all of the nitrogen is converted to ^{22}Ne by the reaction sequence ^{14}N(α,γ)^{18}F(,e^{+} ν_e)^{18}O(α,γ)^{22}Ne. For stars like the Sun, this reaction sequence determines the ^{22}Ne content of the resulting carbon oxygen white dwarf.

It is common practice in the literature to fit white dwarf models without ^{22}Ne to the observed pulsation periods of white dwarfs. This fitting process involves adjusting the composition profiles of a white dwarf model. Thus, fitting the observed periods reveals the hidden chemical stratification of the white dwarf.

Does the ^{22}Ne produced during helium burning impact the periods of pulsating white dwarfs?

To help answer this question, a JINA-CEE team led by Morgan Chidester of Arizona State University explored the pulsation periods of white dwarf models due to the presence, absence, and enhancement of ^{22}Ne. They discovered the average period shifts by about 0.5% due to ^{22}Ne.

Is this shift important? The observed pulsation periods of white dwarfs in the era of the Kepler and TESS missions are typically given to 6–7 significant figures of precision. The typical fit to the observed periods, using models without ^{22}Ne, have a mean error of about 0.3%. Morgan's finding suggests that a systematic offset may be present in the fitting process when ^{22}Ne is absent. This study can provide new inferences on the hidden chemical profiles of white dwarf stars, and new constraints on the nuclear reaction rates that produce those profiles.

Further reading:
Morgan Chidester et al 2021 ApJ, accepted, in press: https://ui.adsabs.harvard.edu/abs/2021arXiv210108352C/abstract

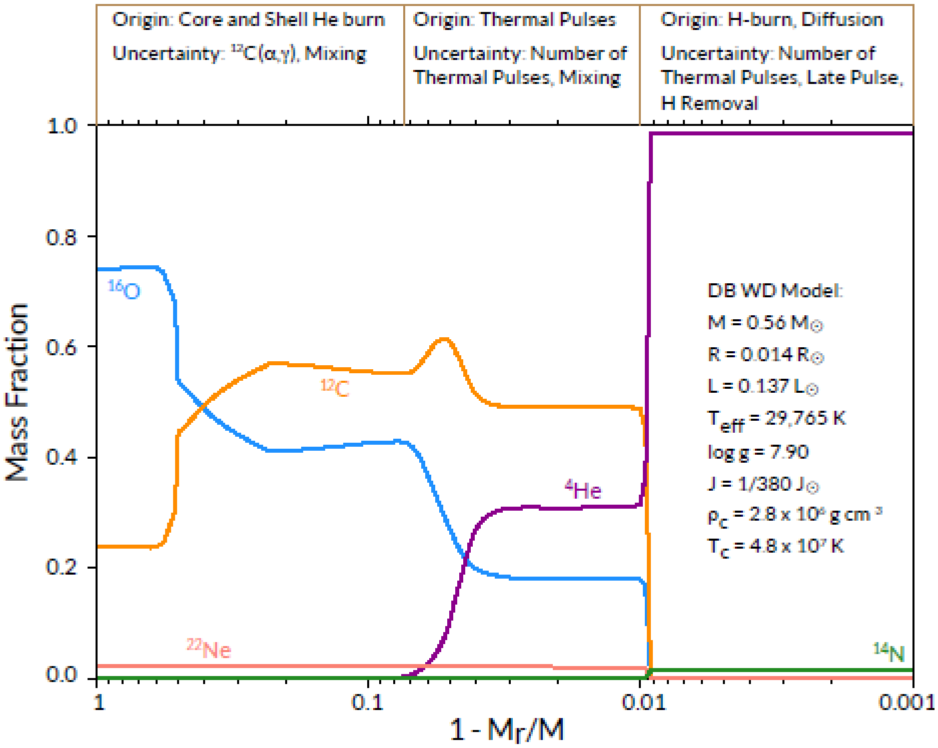


Figure 1. Composition profiles of a typical white dwarf.

The most metal-poor globular cluster in the Milky Way's interior

Excerpt from press release originally published by Carnegie Science

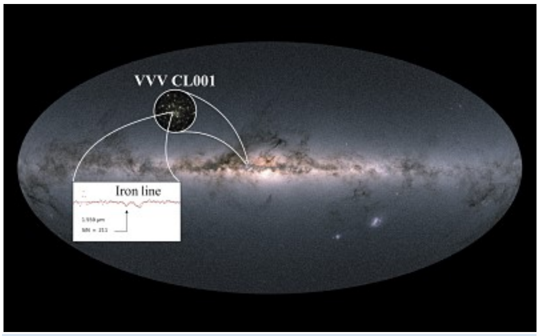


Figure 1: Location of globular cluster VVV CL001 in the Milky Way.

Globular clusters are groupings of thousands, or even millions, of ancient stars. They have existed since the earliest epochs of galaxy formation and are considered important systems that provide relevant clues about their parent galaxies. Our Milky Way is home to a unique collection of more than 150 of these ancient systems. A significant fraction of them reside in the inner regions of the galaxy and move in confined orbits a few kpc (< 26,000 light-years) within the Sun's orbit. In these inner regions of the Milky Way more than a hundred globular clusters have been studied and discovered with an iron content ranging from ~0.5% to 88% of the iron content observed in our Sun.

However, this view has recently changed with the discovery of two red giant stars with extremely low iron content, identified in the innermost regions of the globular cluster VVV CL001. These stars contain less iron in their stellar atmospheres, much less than 0.3% of the iron contained in the Sun. This makes VVV CL001 one of the potential candidates to belong to an exotic and rare family of ancient, extremely iron-deficient globular clusters identified in the interior of our galaxy.

This research was carried out by an international group of scientists that included JINA-CEE´s PI Timothy Beers, and has been published in The Astrophysical Journal Letters. This work uses data from multiple astronomical surveys, including the Vista Variables in the Via Lactea eXtended Survey (VVVX) and the European Space Agency's Gaia mission. In addition, one of the twin spectrographs of the Apache Point Observatory Galactic Evolution Experiment (APOGEE-2) survey, installed on the Irénée du Pont telescope at Las Campanas Observatory, was used.

The very low iron content identified in VVV CL001 places this object at the extreme metallicity limit known to astronomers as the metallicity floor, which has important consequences for understanding the assembly of these systems in the Universe. In the Milky Way, only two globular clusters are known to be in this extreme metallicity regime: VVV CL001, which roams the inner regions of the galaxy, and ESO280-SC06, beyond the orbit of the Sun.

Until recently, a detailed study of the chemical composition of VVV CL001 was not possible due to the large amount of obscuration produced by interstellar matter dust in the interior of our galaxy. However, using near-infrared spectroscopy allowed penetrating the interstellar dust barriers to obtain, for the first time, detailed information on the chemical composition of the interior of VVV CL001.

"Many aspects of our discovery point to VVV CL001 possibly being a satellite ripped from a dwarf galaxy that was completely devoured by the Milky Way more than 10 billion years ago. The finding of very metal-poor globular clusters such as VVV CL001 are atypical in galaxies like ours, and their discovery has important implications for theories of how galaxies form in the Universe," explains lead author José G. Fernández-Trincado (Université Bourgogne – Franche Comté/Universidad de Atacama).

The new stellar spectra provide individual physical characteristics of the stars in the innermost regions of the cluster, such as their surface temperature and gravity, but can also provide their velocity in the radial direction (i.e., we can tell whether they are moving away from or towards us and how fast), and also their chemical composition (for some chemical species such as nitrogen, oxygen, magnesium, aluminum, silicon, and iron) from multiple observations.

New observations with the VVVX near-infrared survey have allowed estimating for the first time an age of about twelve billion years for VVV CL001.

In the interior of the Milky Way, says Fernández-Trincado, there are another hundred or so globular cluster candidates and the goal of the research group is to reveal their chemical history and verify how frequent globular clusters with the properties observed in VVV CL001 are, as well as to know what implications they have on the formation scenario of our Milky Way and other galaxies similar to ours in the Universe.

Further reading: Fernández-Trincado, J. et al., ApJ 908:L42 2021 https://doi.org/10.3847/2041-8213/abdf47

Constraining Nuclear Level Densities for Insight into Ultradense Matter

Contributed by Zach Meisel (Ohio University, USA)

Type-I X-ray bursts on the surfaces of accreting neutron stars provide a unique window into the nature of matter at ultrahigh densities. One avenue for understanding dense matter properties could be X-ray burst model-observation comparisons. However, uncertain nuclear physics inputs limit the viability of this approach. A particularly key reaction is proton-capture gamma-emission, (p,γ), on the nucleus copper-59 (^{59}Cu). Depending on the rate of this ^{59}Cu(p,γ) reaction, energy generation during the X-ray burst may briefly stall, or not, impacting the shape of the burst's X-ray emission over time known as the light curve [1]. The abundance of mass 59 nuclides on the neutron star surface is also impacted, which can alter predictions of the outer neutron star thermal structure [2].

At present, ^{59}Cu(p,γ) cannot be measured directly in the laboratory due to the short lifetime of ^{59}Cu and challenges in radioactive ion beam production. Instead, theoretical calculations are required. A statistical approach known as the Hauser-Feshbach formalism has generally been used for this reaction. However, this assumes a substantial number of nuclear levels are available to be populated when a proton fuses with ^{59}Cu to make zinc-60 (^{60}Zn). Ohio University graduate student Doug Soltesz led the first measurement of the ^{60}Zn nuclear level density. The measurement, performed at the Edwards Accelerator Laboratory at Ohio University, involved impinging a 10 MeV beam of helium-3 (^{3}He) onto a nickel-58 (^{58}Ni) target and detecting the spectrum of neutrons evaporated from this reaction. The neutron energy spectrum was related to the ^{60}Zn level density, taking advantage of the fact that evaporation populates final levels statistically. More neutrons detected with a given energy means more levels are present at the corresponding excitation energy in ^{60}Zn.

Our results show that the ^{60}Zn level density is on the boundary of Hauser-Feshbach validity for the excitation energy region of interest for X-ray bursts (see Figure 1 left panel). This means that measurements of the quantum mechanical spin of the relevant levels, or just the spin distribution, are now necessary in order to determine how many astrophysically-relevant levels are present (see Figure 1 right panel). Our results also show an interesting plateau in the nuclear level density in the ^{60}Zn excitation energy region of interest, contrary to the exponential increase expected from nuclear theory. This is the second observation of such a plateau, which is not presently understood theoretically.

Further reading: D. Soltesz et al. Phys. Rev. C, 103, 015802, 2021.

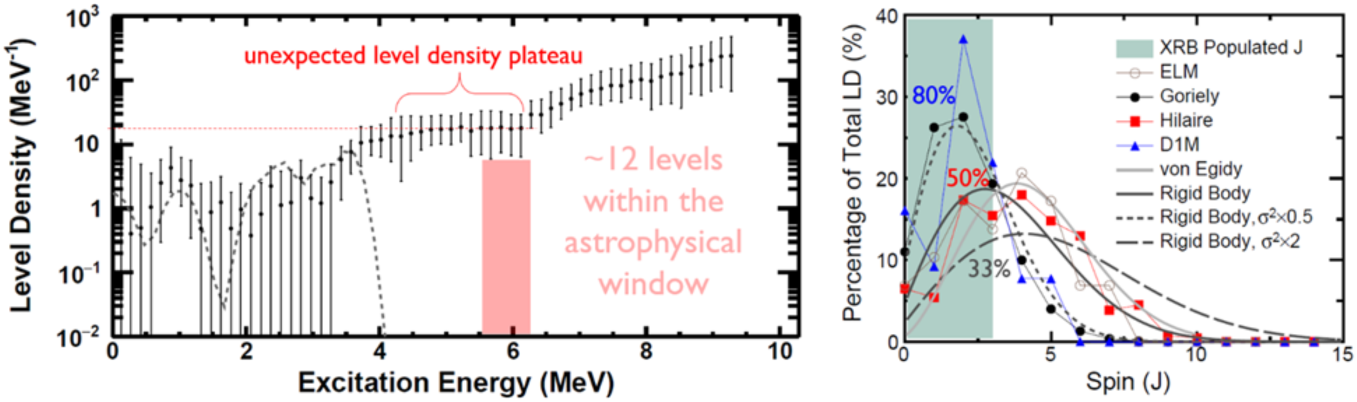


Figure 1: The left panel shows the measured level density of ^{60}Zn, where the excitation energy region of interest for ^{59}Cu(p,γ) in X-ray bursts is highlighted. The right panel shows theoretical estimates of the spin-distribution for levels of ^{60}Zn within the excitation energy region of astrophysical interest. Green shading indicates the spin-range for astrophysically relevant states. The percentages indicate what fraction of levels would be within this range for different theoretical spin-distribution models.

References:

[1] Meisel, Merz, & Medvid. Astrophys. J., 872, 84, 2019. (See March 2019 JINA Newsletter)

[2] Meisel & Deibel. Astrophys. J., 837, 73, 2017.

JINA-CEE Faces:
Interview with Erika Holmbeck

Erika Holmbeck,
Rochester Institute of Technology

Erika Holmbeck was born and raised in California, and recieved her undergraduate degree in astrophysics from the University of California Los Angeles. She joined the University of Notre Dame in 2015 to study nuclear astrophysics alongside Rebecca Surman and Timothy Beers, and completed her PhD in 2020. Erika currently works as a postdoctoral researcher at the Rochester Institute of Technology in New York. Erika has been selected as one of the 24 NASA Hubble Fellows of 2021, a very prestigious program that supports outstanding postdoctoral scientists for up to 3 years to pursue independent research that contributes to the NASA Astrophysics division. She will start her fellowship this fall at Carnegie Observatories. Her proposal "The R-Process Refinery: Distilling Stellar Signatures to Characterize the Astrophysical Production Site of the Heavy Elements" was selected to help answer one of NASA's big questions about the universe: How did we get here?

Could you tell us what becoming a NASA Hubble fellow means to you?
-Earning one of these fellowships is extremely validating. Clearly someone else believes my research is worth funding and supporting. I plan to stay in academia long-term, and this fellowship increases that possibility and opens the door to new opportunities.

When did you decide to pursue a career in science?
-I've been interested in science for as long as I can remember. Both my parents worked in the aerospace industry, so that exposure had something to do with my interest in space. I had considered studying genetic engineering for a while in high school, but then decided on astrophysics, always with the idea of figuring out how elements are made in the cosmos.

How do you interact with JINA-CEE?
-I actually found out about JINA for the first time when I was looking for graduate schools through Google. I intentionally applied to schools where I could work with JINA researchers, so from the start my entire graduate career has been defined by interactions with JINA-CEE. Most of my collaborators are JINA-CEE members, and I take every opportunity to participate in events where I can interact with the community. I also co-organized the First Frontiers Summer School for undergrad and grad students a couple of years ago.

What is the focus of your research?
-I study how the heaviest elements, actinides in particular, are made through the r-process. I like to think about my research as "stellar genealogy" because I study how the oldes stars have influenced later stellar generations throughout time. I use nucleosynthesis simulations to determine elemental abundances in different cosmic events and I also observe those elements in metal poor stars so that I can compare the observational data to the theory.

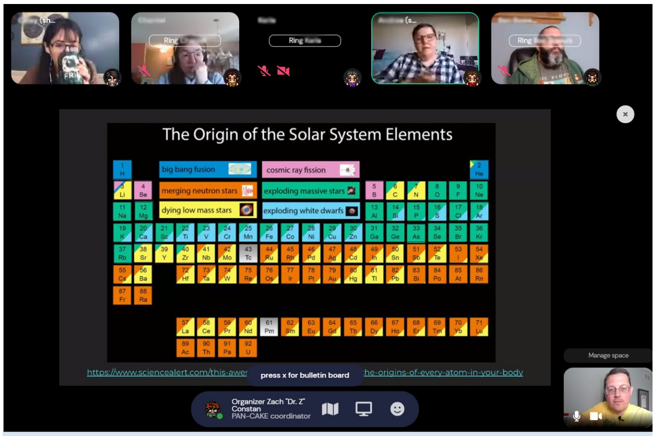
What is your scientific finding that you are the most proud of?
-Probably in my most recent paper: Reconstructing Masses of Merging Neutron Stars from Stellar r-process Abundance Signatures, where we used observed abundance patterns to uncover some physical properties of neutron star mergers themselves. For this work we needed to consider nuclear data, the nuclear equation of state, galactic chemical evolution, population synthesis, and stellar abundances. So this work is a multidisciplinary —and unique— approach to the origin of the elements.

What's your advice for junior researchers?
-Don't be afraid to ask questions or to pursue what you are really interested in. It is very important to find the topic that most excites you. Secondly, it's challenging to just "be confident," so rather, have conviction and trust yourself and your research. Lastly, be mindful of keeping a work-life balance. I think that it is important to do something creative outside your work.

Physics of Atomic Nuclei Classroom Activities for Educators (PAN-CAKE) 2021

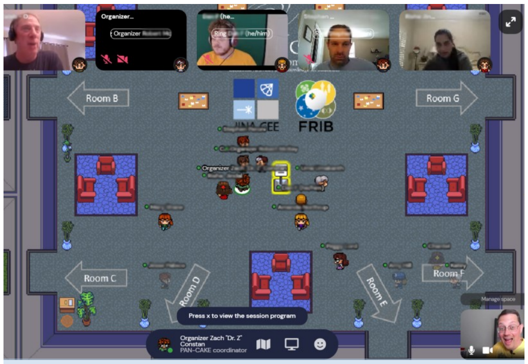
Contributed by Zach Constan (Michigan State University, USA)

A condensed online version of JINA-CEE's Physics of Atomic Nuclei (PAN) program hosted ~40 science teachers from twenty US states and Canadian provinces in March 13-14. The "PAN-CAKE" program took advantage of the innovative virtual learning strategies JINA-CEE has developed to provide a free professional development course that was accessible and convenient to fit around a school's schedule. Eighteen volunteers representing JINA-CEE and FRIB worked alongside expert educators to design educational activities that equipped participants with the knowledge, tools, resources, and confidence necessary to incorporate nuclear astrophysics in their own classroom:



Research fair presentation on nucleosynthesis.

- Greg Severin's talk, titled "FRIB: Smashing Atoms with a Purpose", gave participants an overview of the laboratory, and highlighted how FRIB allows researchers to advance both societal applications and our fundamental understanding of the universe.
- In her talk, titled "Cooking up the Elements in Stars and in the Laboratory", Artemis Spyrou discussed the astrophysical observables that give us clues into how the Universe works, and the nuclear physics input that help us piece together the puzzle of the origin of the elements.
- Participants were able to explore the FRIB laboratory on a virtual tour led by Zach Constan. Using 'photospheres', they had exclusive access into research spaces and many locations that would normally be inaccessible during an in-person visit.
- "Discoveries before College", a talk by Paul Gueye, provided examples of strategies teachers could use with minimum effort and maximum impact to inspire students to pursue STEM careers.
- The Research Fair showcased short presentations on current work by research groups at FRIB and/or JINA-CEE. Topics included fission, decay modes, mass measurements of rare isotopes, types of dectectors and techniques for nuclear physics experiments, decay spectroscopy, astrophysical models and observations, nucleosynthesis and more.
- The Education Fair included presentations on ways to incorporate nuclear science and astrophysics into the high school curriculum. Topics included Rutherford scattering, nuclear structure, a preview of TINA (Training in Nuclear Astrophysics) — a new concept that makes research grade code and cutting edge topics available to the public for self-guided learning—, opportunities for students, tools, demonstrations and ideas for classrooms, plus many more educational resources.



Coffee break at the virtual venue in gather.town

The recorded and live presentations from faculty were coupled with breakout discussions and Q&A sessions to encourage two-way communication with teachers. In the post-survey, all participants agreed that PAN-CAKE was useful and made them more interested in teaching nuclear science/nuclear astrophysics. They would also recommend the program to other teachers.

PAN-CAKE served twice as many teachers as any previous PAN program, which will impact the students they inspire for years to come. Many thanks to all of the volunteers who spent part of their weekend to promote nuclear astrophysics education!

Anna Watts is awarded the 2021 AAS HEAD Mid-Career Prize


Anna Watts, University of Amsterdam, NL

We are pleased to congratulate our collaborator Anna Watts, professor of astrophysics at the University of Amsterdam, for being awarded the 2021 American Astronomical Society High Energy Astrophysics Division's Mid-Career Prize: "for her trailblazing work in the understanding of neutron star fluid dynamics, and developing and applying rigorous inference to obtain observational constraints on dense matter".
The HEAD Mid-Career Prize is awarded approximately every 18 months for a significant advance or accomplishment (observational or theoretical) in High Energy Astrophysics by an individual astrophysicist within fifteen years of receiving their PhD. The prize is selected and administered by the AAS HEAD Executive Committee.

"*This is such a nice thing to happen, I'm incredibly honoured! But by mid-career it's not just down to you but your team as well, and I've been beyond lucky with the junior researchers in my group - so this is for them too, you're all awesome!*", said Anna about the award.

Further reading: https://head.aas.org/midcareer/midcareer.prize.html

JINA-CEE Institutions

JINA-CEE Core Institutions:
Michigan State University
University of Notre Dame
Arizona State University
University of Washington

JINA-CEE Associated Institutions:
Alabama A&M University, Arkansas University At Pine Bluff, CCAPP Ohio State University, Central Michigan University, ChETEC, CNA Shanghai Jiao Tong University China, Dillard University, EMMI-GSI Helmholtz Gemeinschaft Germany, Florida State University, Howard University, INPP Ohio University, Los Alamos National Laboratory / LANSCE-3 / T2, Massachusetts Institute of Technology, McGill University Canada, MoCA Monash University Australia, National Astronomical Observatory of Japan, North Carolina State University, NUCLEI LANL, Argonne National Laboratory, Princeton University, Rutgers University, Texas Southern University, TRIUMF Canada, University of Amsterdam Netherlands, University of Chicago, University of Hull UK, University of Minnesota, University of Oslo Norway, University of Texas Rio Grande Valley, University of Victoria Canada, Virginia Union University, Western Michigan University.

For a full membership directory see the JINA-CEE website.

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For comments or questions about this Newsletter and other JINA-CEE related issues contact :
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